FEASIBILITY OF FRM FOR THE RECONSTRUCTION OF AN ANCIENT ROMAN TEMPLE

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OUTLINE

- Introduction
- Assessment of the authentic materials
- Fiber-reinforced mortar studies at UNL
- Feasibility of FRM for the Temple project
- Concluding remarks

INTRODUCTION

2005-Collapsed State of the Temple

2005-State Plan with
270 surveyed blocks on
the surface

The ultimate goal is to reconstruct the temple (most likely a partial reconstruction)

INTRODUCTION

- Collaboration of Architectural Engineering and Archeology/ art history:
  - To “reconstruct” the original design
  - To understand the construction technology employed at the time
  - To assess the condition and capacity of remaining structural elements and materials
  - To design an appropriate reconstruction scheme: “big picture” & details (materials)

INTRODUCTION

3rd Century A.D.

"Hard Hat Archeology"

INTRODUCTION

INTRODUCTION

- Summers 2007 & 2008:
  - Before Blocks are moved they are evaluated
    - Measured
    - Sketched
    - Surveyed *in situ*
    - Digital database formed: assessments and photos, soon drawings will be added
  - Blocks are assessed in order to determine:
    - The block's role in the structure of the temple
    - Its ability to be used in reconstruction
  - Site is assessed to discover what is underneath

INTRODUCTION

Putting the pieces of the puzzle together… first architecturally…

INTRODUCTION

Putting the pieces
of the puzzle
together…
Then historically…

Temple: 3rd Century A.D.

Medieval intervention?

INTRODUCTION

In the mean time… we need to do structural and material assessment s…

Marble block assessments

1

2

3

4

INTRODUCTION

In the mean time… we need to do structural and material assessment s…

Mortar Assessments

INTRODUCTION

In the mean time… we need to do structural and material assessment s…

Mortar Assessments

INTRODUCTION

Goals of this particular sub-study within the temple project (i.e. the paper/presentation):

- Characterization of the authentic mortar with an ultimate goal of finding appropriate and novel repair methods for the structural system

- Evaluation of the feasibility of using Fiber Reinforced Mortar (FRM) in the repair of the temple's foundation walls and the platform.

MORTAR CHARACTERIZATION

2 groups of tests in 3 laboratories are utilized in three laboratories thus-far on authentic mortar samples:

- Mechanical Properties at UNL labs
- Chemical, microscopic, and Differential Thermal Analysis (DTA) tests at two independent laboratories (one in U.K. and one in the U.S.

MORTAR CHARACTERIZATION-1

Samples used in the mechanical and chemical tests

MORTAR CHARACTERIZATION-1

Mortar samples for Compressive test
(2in x 2in x 4in = 5 cm x 5cm x10 cm)

MORTAR CHARACTERIZATION-1

	Specimen #	T-R-C1-08	T-R-C2-08	T-R-C3-08	T-R-C4-08
Area	(in^2)	4	4	4	4
	(cm^2)	25.8	25.8	25.8	25.8
Weight	(lb)	0.891	0.799	0.977	0.9375
	(N)	3.96	3.56	4.35	4.17
P_{max}	(lb)	2,980	2,320	1,740	1,970
	(N)	13,261	10,324	7,743	8,767
Comp. strength (f'_c)	(psi)	745	580	435	492
	(Mpa)	5.14	4.00	3.00	3.39

T-R-C1-08 Designation: Temple- Roman Period- Compressive Test1- 2008

MORTAR CHARACTERIZATION-1

	Specimen #	T-R-C1-08	T-R-C2-08	T-R-C3-08	T-R-C4-08	Average
Comp. strength (f'c)	(psi)	663		464		**563**
	(Mpa)	5		3		**3.88**
Condition		(less voids and vegetation)		(more voids and vegetation)		

A quick comparison to modern mortar standards…Despite use of cement:

- Type O in US (1 part Portland cement: 2.5 part hydrated lime/ lime putty)→ f'c = 350 psi (2.4 Mpa) – typically not allowed for load bearing

- Type N in US (1 part Portland cement: 1.25 part hydrated lime/ lime putty)→f'c = 750 psi (5.17 Mpa)

MORTAR CHARACTERIZATION-2

Wet Chemical Analysis (Test Center 1- U.S.)

- Mortar sample with a diameter of about 1 in . (2.5 cm) is weighed and crushed
- Dissolved in a 3:1 water & Muriatic acid solution
- Aggregates that are left are weighed and the lime binder to aggregate ratio is determined
- Aggregates are then sieved through different size sieves

MORTAR CHARACTERIZATION-2

- Colours:
  - Mortar in general light grey comparable to Munsell 2.5Y-8/1 to 7/1.
  - The colour of the sand (Munsell based): 2.5Y-7/1 to 6/1
  - The colour of the fines (Munsell based): 2.5Y-7/2

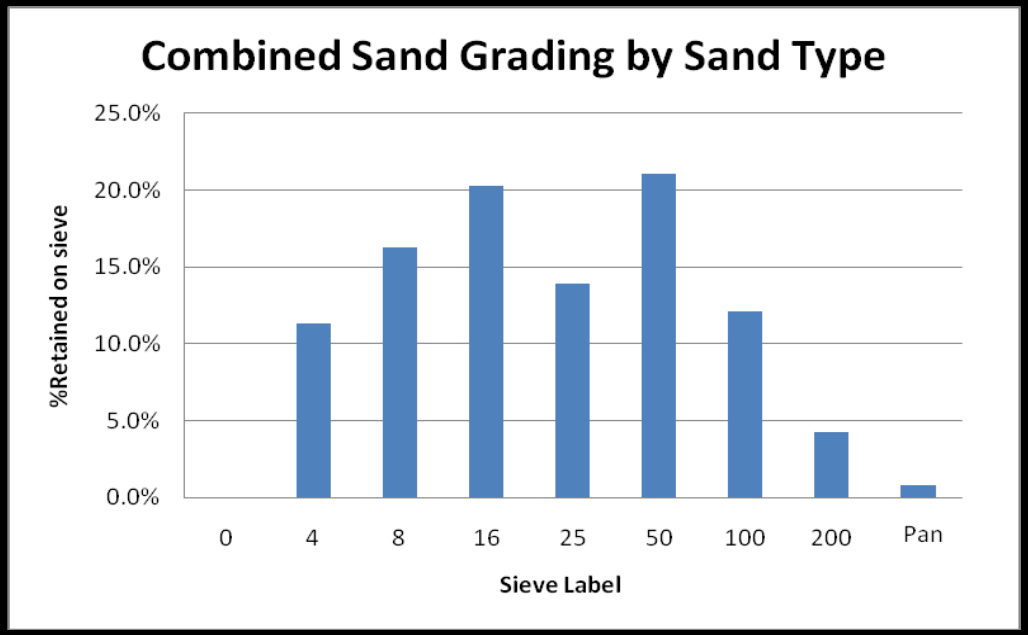
MORTAR CHARACTERIZATION-2

- The original weight of the sample was 15.71g.
- After being exposed to the soluble acid the following weights were determined:
  - Weight of sand: 9.26g
  - weight of fines (the particles that are left in the pan after the sieving process, noted as pan in **Fig.** 4): 7.85g
  - Soluble Fraction Weight (Lime): 4.60g
- The Proposed Original Mix (dry weight ratio): 2.42:1 sand and fines to lime

MORTAR CHARACTERIZATION-2

Aggregate Analysis Results

Sieve Label	0	4	8	16	25	50	100	200	Pan	
Sieve size (mm)	0	4.75	2.36	1.18	710UM	300UM	150UM	75UM	pan	TOTAL
Sample (grams)	0	1.05	1.51	1.88	1.29	1.95	1.12	0.39	0.07	9.26
Percent	0.0%	11.3%	16.3%	20.3%	13.9%	21.1%	12.1%	4.2%	0.8%	100.0%



MORTAR CHARACTERIZATION-3

- 2 separate samples
- Chemical, microscopic and differential thermal analysis (DTA) applied
- Results almost identical

MORTAR CHARACTERIZATION-3

- 1 part Lime : 2-2.5 part sand

- Aggregate almost entirely soluble limestone sand
- 1.1% insoluble aggregate is yellow/brown clay

- Binder: Carbonated lime. No pozzolanic additive.

- Microscopic inspection reveals crystal (calcite) growth

MORTAR CHARACTERIZATION

Summary-1:

- Lime: Sand ratio is around 1: 2.5
- This finding agrees with literature

- Virtuvius on Romans mortars: 1: 3 and 1: 2 but notes pozzolan use.
- A study of historical mortars in Turkey state that a variation of lime mortar called Horasan Mortar was found.
  - Made of lime with varying proportions of river sand, brick pieces or powder
  - Very strong

MORTAR CHARACTERIZATION

Summary-2:

- Weak/soft mortar in composition
- No cementitious or pozzolanic additive
- But relatively durable! (parts crushed powder, parts completely intact in chunks).
- Very reactive in chemical analysis
- Carbonation is not surprising. It has aged over centuries.
- Clay is not a surprising fine aggregate as the site's typical soil is clay.

MORTAR CHARACTERIZATION/ REPAIR

- Other studies also confirm that up to a ratio of 1:3 lime to sand by volume exist in historic context with inclusions of other aggregates such as:
  - Crushed marine shells (another source of lime)
  - Brick dust
  - Clay
  - Natural elements
  - Pigments
  - Animal Hair

RECONSTRUCTION/ REPAIR

- Potential Repair, Reconstruction, and Strengthen Techniques
  - Repair mortars for platform and foundation walls
    - Fiber Reinforced (Lime) Mortar(FRM) is considered
  - Epoxy injections in the cracks
    - Regular and Fiber Reinforced thin mortar/epoxy are considered
  - Joining marble blocks, column drums, etc…
    - Fiber reinforced polymer bars or ties are considered

REPAIR MORTAR: FRM?

Preliminary composition considerations

- 1 part lime putty (properly matured)
- 2-2.5 part yellow limestone sand (< 3.35 mm)

+

- Polyvinyl alcohol (PVA) micro fibers

REPAIR MORTAR- FRM?

- Cause of failure: most likely earthquake (article on earthquakes in the region at antiquity) OR religious wars
- Structure is high on a hill and have high walls and columns→ weak for wind loads as well

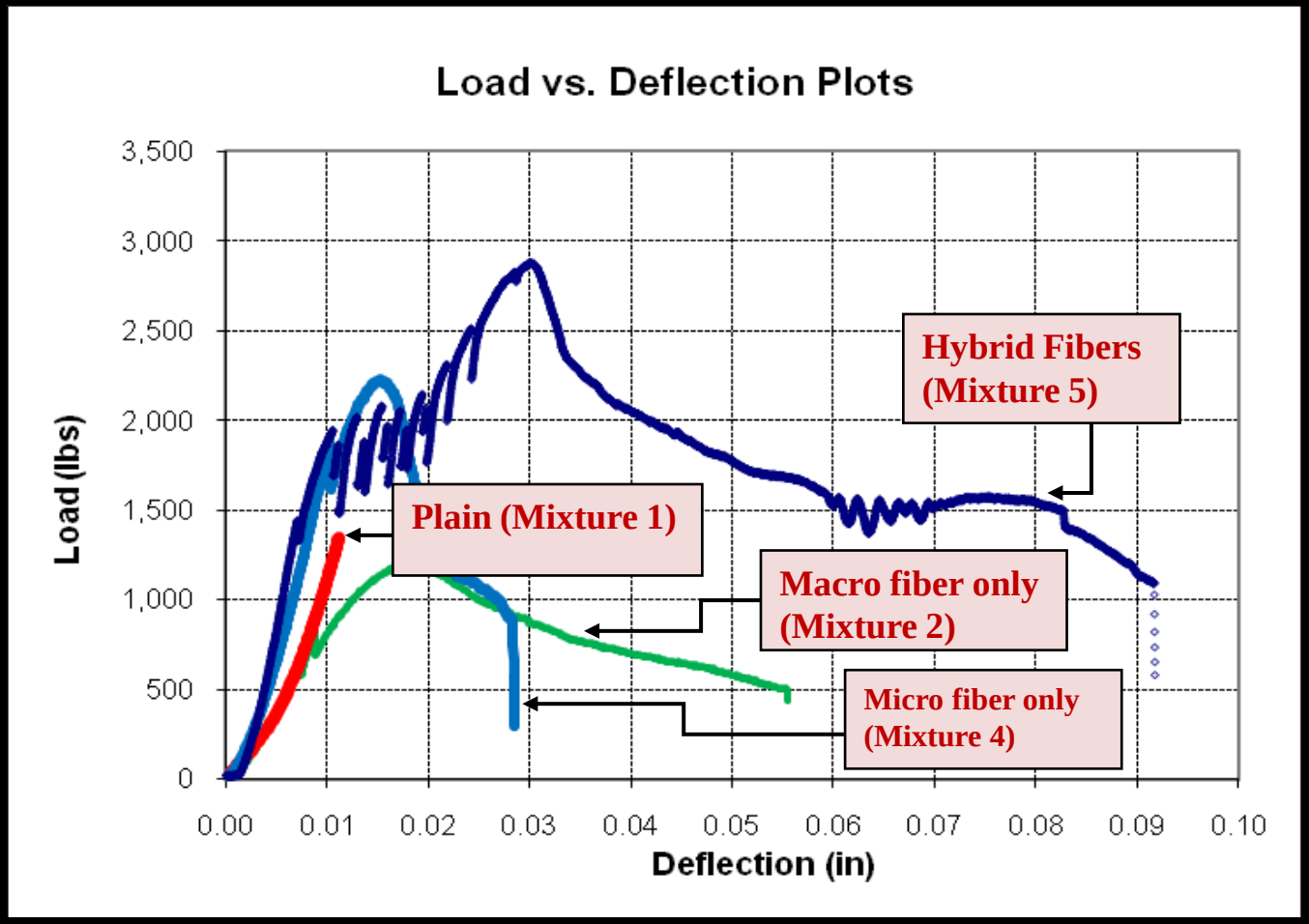
Thus,

- More tensile strength is needed

However,

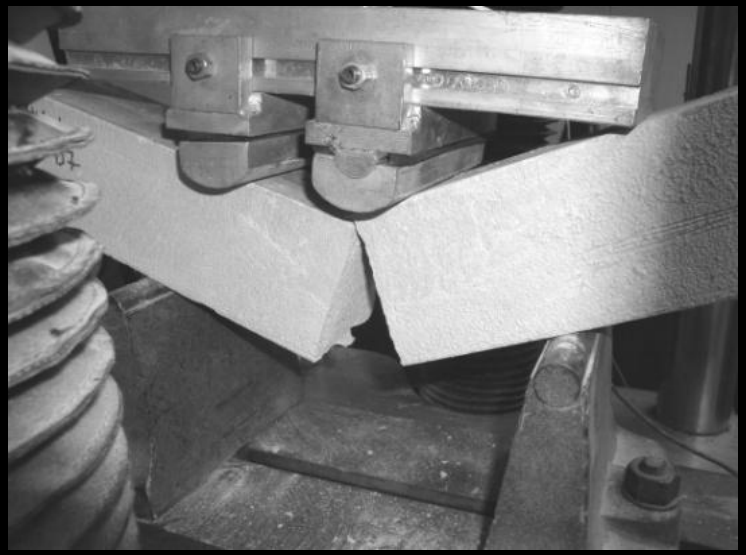
- Mortar should not be stronger than needed for the structural strength in compression
- Must be durable: requirements of the masonry

REPAIR MORTAR



Comparison of Load Displacement Curves between Plain Mortar and PVA- FRMs

REPAIR MORTAR- FRM?



REPAIR MORTAR- FRM?

Bond strength & flexural tensile capacity very much improved with the right mixture- good

Mixture ID	$f_{r\text{-}pris}$ (psi)	$f_{r\text{-}pris}$ (MPa)
Mixture 1- Plain	78	0.54
Mixture 2- PVA 1	92	0.63
Mixture 3- PVA 2	83	0.57
Mixture 4- PVA 3	111	0.76
Mixture 5- PVA 4	88	0.61
Mixture 6- PVA 5	78	0.54
Mixture 7- Corn silk	181	1.24

REPAIR MORTAR- FRM?

Not a direct affect on compressive strength- also good

Mixture ID	f'c (Mpa)
Mixture 1- Plain	6.2
Mixture 2- PVA 1	4.4
Mixture 3- PVA 2	5.4
Mixture 4- PVA 3	6.7
Mixture 5- PVA 4	9.4
Mixture 6- PVA 5	5.5
Mixture 7- Corn silk	N/A

CONCLUDING REMARKS

Preliminary REPAIR MORTAR composition

- 1 part lime + 2.5 part yellow limestone sand (< 3.35 mm) + PVA micro fibers → micro-FRM

- TESTING IN PROGRESS FOR MOCK SAMPLES AT UNL LABS
- Literature shows promise for lime mortar + fibers
- Optimization and future work needed

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